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CONTROL SYSTEM OF NUCLEAR REACTORS

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Nuclear reactors under development nowadays differ greatly in purpose, power and construction so that an individual control system has to be designed in every case. At the same time all kinds of reactors must be extremely reliable when operating. Only reliable control systems are able to ensure reactor safe operation so a great attention is paid to the control systems design. In doing so the designers of reactors tend to provide safe operation at minimum investments.

Two phases of control. One of the main factors of control systems is a permitted rate of changing the power level of a reactor. In practice it is desirable to get a maximum rate of changing the power level but due to specificity of reactors the rate of changing the power level is always limited by safety requirements. That increases the time taken to attain or change a desired power level. Research reactors with neutron fluxes about $10^{15} \div 10^{16} \frac{N}{sm2sec}$ should be started and attain the full power within approximately 30 min. after shutdown otherwise an intensive poisoning of the shutdown reactor will start. Autonomous nuclear power plants should be started and attain a desired power level within approximately 15 min so as usual they have no reserve power supplies and within the interval the steam produced at the expence of accumulated energy can be used by the plants themselves. In these cases a compromise solution should be found to guarantee safety of the power plants and operation without failures.

To minimize the time taken to attain the full power level the reactor power should be increased exponentially. However such an increasing of the power is not permissible at many reactors in the full range of the rated power. Power plants and research power reactors can be brought exponentially up to the power level only of some percents of the rated power, that is, in the range of changing power where the heat generated in a reactor can be effectively removed and where dangerous temperature drop cannot arise.

At higher levels the power of a reactor should correspond to the rate of coolant flow but the rate of power changing is limited in order to avoid a thermal shock. In this power range from our view-point a ramp power increasing is most advisable.

The requirement to minimize the time of attaining a power level and that of safety and convenience of operating can be fulfilled while startup and at low power levels power increasing will be exponential and in the range of rated power the increasing will be ramp. In accordance with it all the controlled range is divided in two parts: startup range and operating range. A startup control system is to operate in the range from a shutdown to 1÷10% of the rated power and an operating control system is to operate in the range from 1÷10% to the full rated power. The moment of passing from the startup control system to the operating control system is determined in any single case.

Main system functions. A startup control system is to measure the power on a logarithmic scale and the period of a reactor. Besides it has to insert excess reactivity for compensation subcriticality and bring the reactor to a demand power level with a desired period and then maintain the attained power level. It has also to generate approach signals used for corrective actions of the system and signals of scram protection in the case of exceeding a demand rate of power change or demand power level. The accuracy of controlled period and power level of a startup system may be 20÷25% of a demand value.

An operating power control system is to measure, correct and change power levels and take care of all changes of reactivity. It has also to generate approach signals used for corrective actions of the system and signals of scram protection at over power levels.

The accuracy of maintaining a power level is usually of 1% of the rated power. Within the operating range generation of over-power-level signals is produced by an over-power-level system. The system can generate a signals at absolute or relative over-power-levels in the full range of its operation.

From our point of view it is desirable to use an absolute control power system. At the rate power level it is difficult to decide what system is preferable but at low levels the sensitivity of the absolute control power system is less than that of the control power system responding to relative over-power-levels. Decreasing sensitivity reduces the probability of arising scram signals due to small over-power-levels which are not dangerous for a reactor and that makes the system more reliable. Besides one can simplify the system so as the system gain need not be a function of power level and so the sensitivity threshold may be set one hundred times as high if the system has a power range of two decades. Such simplification tends to increase reliability of the system.

Signals of exceeding the rate of power level changing or that of over power level from the startup control system and over power level signals from operating control system are fed to circuits of forestall and scram protection. The circuit of forestall protection warns the operator about deviation of controlled parameters and permit rod motion in the negative reactivity direction only. The circuit of scram protection inserts different number of rods depending on fault circumstances and shuts down the reactor.

Since the operating levels are within two decades and the system of automatic shutdown is rather quick operational an over-power-level signal is sure to cause a shutdown before the peric becomes dangerous. That is why in the operating range protecti of the reactor in the case of exceeding the power change rate is not provided as a rule.

The operating control system should be extremely reliable so as it controls the reactor under high power density conditions and besides the operating control system is designed to operate for a long time in contrast to startup control system. At least two automatic power controllers and three independent over-power--level control channels provide necessary reliability. The per-

formance of several independent duplicating channels should be accorded. Automatic equipment should be convenient for maintenance and foolproof.

Power demand loop requirements. Power demand signals are fed to every channel of automatic and over-power-level control. The signal is compared with that of from the ionization chamber which is a power measuring element. If there are independent power demand loops in every channel the operator changing a power level should take a number of manipulations which are sequence of reference adjustments in every channel and that results in eliminating unbalance of corresponding devices. It is important to keep an order in setting references that is if a power level is to be increased the reference of the over-power-level channel should be changed first and then the reference of the operating and redundant automatic control channels. If a power level is to be lowered the opposite action is taken. It should be so otherwise there may be unnecessary shutdowns. In such a way of setting references great power changes are undesirable because of considerable over-power level sensitivity reducing and therefore reducing safety of the reactor.

A lot of manipulations taken by the operator attract him away from fulfilling other tasks. Reliability of the system and safety of a reactor to a great extent depend on training of the operator and his incorrect actions may cause unnecessary shutdowns.

The conventional power demand loop consists of a number of switched resistors (switched power demand loops) and potentiometers or continuously variable transformers with manual control (continuously variable power demand loops). Changing of power demand in switched power demand loops results in automatic controller cutoff due to arising a great misalignment.

Continuously variable power demand loop usage gives an opportunity to change the reactor power followed by the change of power demand but the range of permitted power demand settings is limited because great misalignments may also cause automatic controller cutoff (misalignments as usual are about 20% of a demand power level).

If the automatic control system does not follow the power demand changings the operator should change a power level with manual rods while the automatic control system should be cut off. That also reduces the safety of the reactor so as the operator incorrect actions may cause increasing the power of the reactor with dangerous rate.

From the foregoing analysis we can come to the conclusion that the operating control system should have a common power demand loop where a power demand setting is changed continuously and the rate of changing power demand is independent on the operator. Besides there should not be such difference between the power demand reference and the signal that results in automatic controller cutoff. Choosing the rates of changing power one should always remember the main conditions of heat transfer.

Such a power demand loop in combination with an automatic controller will result in reactor power following the power demand setting and the over-power-level setting following the automatic controller setting.

<u>Design principle of power demand loop</u>. Taking into consideration the significance of functions of power demand loop and the fact that the power demand loop operating in the system is single it is exceedingly important to guarantee a reliable power demand loop performance.

Maximum increasing the reliability of the power demand loop results in the reliability of the system at the expence of simplification the power demand loop, reliable elements application and redundancy; for example, the outputs of two power demand loops are shunted through a logic diod circuit "or". If the voltage at the output of one power demand loop disappears the voltage at the common output of the system will not change. The blok diagram of the power demand loop is shown in Figure 1.

The main power demand loop element is a mag-slip 1, drived by an electric motor 6 (unit IV). The voltage between the phases of the mag-slip winding is a function of rotary motion. This voltage via the control range selector 9, transformers 11, 12, 13 is fed to the power demand loop output. A direct current sig-

nal from the outputs of the transformer with rectifiers is fed to the power demand indicator 14, via the logic circuit "or" 10' to the circuits 16, comparing the reference currents with the ionization chambers currents 15 and via the circuit "or" 10" to the circuits adjusting the gain of the controller amplifiers VII to give the same automatic controller sensitivity in the full range of power demand loop performance. A direct current signal from the rectifier 12 via the circuit "or" 10"' is fed to the over-power-level control channels. An alternative current signal from the transformer 11 is fed to the switching and cpmparing circuit (3) of servosystem unit III.

The range of changing power demand output currents is 300 microamperes and corresponds to the ionization chamber currents from 2 to 600 microamperes for the automatic controllers and from 1 to 300 microamperes for the over power level control channels. These currents correspond to the reactor power range from 0.5 to 150% of rated power N_{nom}. If the rate of the power demand changing is the same in the full range it turns that in practice it is impossible to meet two conflicting requirements: minimum time taken to attain other power level and safety of power increasing. If the safety of power increasing is provided that is short periods at low power levels are impossible it will take too much time to change a power demand setting which from practical view-point is unacceptable.

It is reasonable to separate the operating power demand range in two parts: the first range corresponding to 0.5÷15% and the second one corresponding to 15÷150% of the rated power. A mean effective voltage between phases of three-phase mag-slip winding in the power demand loop is a sine function of the rotary motion relative to the stator. Separation use is made of connecting different mag-slip phases to the output circuits. The slewing angle in each range does not exceed 60° and that practically provides a linear characteristic of the output voltage as a function of rotary motion.

Shown in Fig.2 theoretical current curves at the outputs of the power demand circuits are functions of mag-slip rotary motion and power demand. There are also shown the ionization

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chamber currents as functions of reactor power in the first I and second II ranges for the automatic controller and over-power-level channels while power demand circuit operating.

The curves of power demand loop currents changing and input currents of amplifiers while switching the ranges are shown in Fig.3.

While transiting from the first range I to the second one II the current fed to the automatic controller channels drops off by a factor of 10 and that is why the ionization chamber current should also be reduced by the same factor. That is made by connecting a shunt resistor to the input of the controller amplifier.

The power demand current function of rotary motion for over-power-level control channels is continuous throughout the full range of power demand loop operation. The function is shown in Fig. 2b.

The required output signal dependence on mag-slip rotary motion is provided by use of a ballast resistor in the output circuit of the first range I, the output signal magnitude remaining the same while switching the phases.

The output currents fed to the over-power-level control channels in intermediate positions 2 and 3 of the range selector may be only increased and that is why while switching the ranges false emergency signals cannot arise.

There may be different rates of changing power demand settings in the power demand loop. One of the power demand loop modifications provides the rate 0.02% of the rated power per second in the first range I and 0.2% of the rated power per second in the second range II (under the same rate of rotary motion). Separating the range in two parts results in increasing the accuracy of power demand setting while operating at low power levels. Besides the power demand loop may also provide the rate of changing settings approximately ten times as high as the normal rate. The higher rate of changing settings is used for quick decreasing the power level of the reactor or putting the power demand setting to a required position when control system cut off. In this case the may-slips I and I' are controlled by the separate elect-

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ric motor 6' with its own gearbox.

To prevent the changing of output power demand signals under cutoff or fault of one of two power demand loops connecting in parallel a circuit of compensation is used where the magnitude of blanking voltage in the compensation circuit will be changed if one of the power demand loops is cut off.

A voltmeter with 270° scale is used to indicate an output voltage of the power demand setting.

There are two ranges of the indicator power demand measurements which correspond to the ranges of power demand loop operation. A large scale of the indicator and two ranges of measurement provide content accuracy of reading.

To simplify the maintenance of the system there is a unit of settings I which provides power demand setting. The unit of setting consists of the mag-slip 1. The rotor of the mag-slip is connected with an outer handle. While slewing handle to a desired position (indicated on the scale of the unit) the voltage corresponding to the setting arises at the output of the unit. This voltage is fed to the circuit of selection and comparison in the third unit 3 of the servosystem III where it is compared with the voltages arising at the outputs of the power demand loops. The servosystem driving power demand electric motors provides adjusting the setting of each power demand loop in accordance with said desired position of the handle.

There are also keys 19 of independent power demand control. The power demand loop which key is in operation takes a driving part in performance. The servosystem of the driving power demand loop produces a power demand error signal and driving the motor of the second (driven) power demand loop provides adjusting the setting of the latter in accordance with the setting of the former. In such a way of control the operator has to keep the control key switched on for all time taken to change a power level. When the unit of settings driving, the operator only changes a position of the unit handle.

A signal from the coolant flow control system 2 (instead of that from the unit of settings) may be also fed to the servosystem III. In this case the coolant flow the power of the reactor are changed in step. It is possible also to correct power settings

using signals from the temperature and pressure control systems. When deviating a controlled parameter the relay 5 in the corrector V operates and switches on the power demand loop motors and thus the reactor is being brought up to a demand power level.

Taking into account that there may be mismatches of tuned amplifiers and ionization chamber currents and that there may arrise deviations in the currents of the ionization chambers while operating reactor every channel of the system is provided with separate manual correctors of chamber currents and automatic correctors of power demand setting. The manual correctors of chamber currents are input shunts of the amplifiers and they may change the transmission factor from a chamber to an amplifier up to three times with accuracy no more than 1%. The automatic correctors of setting VI are only in the controller channels and represent a servosystem providing the absence of unbalance at the redundant controller amplifier output. The corrector guarantees the absence of unbalance and therefore the possibility of switching on the redundant automatic controller while fault the operating controller.

The main element of the corrector is a mag-slip 1 which operates as a noncontact induction potentiometer. The angle of the mag-slip rotary motion is limited as well as it is done in the power demand circuit. This angle is 60^0. A mag-slip voltage via the transformer with the rectifier 13 causes the current of correction fed to the comparator 16. The current of correction is a part of the compensation current compared with that of the ionization chamber. A voltage from the separate power demand mag-slip I" is fed to the stator of the mag-slip I"' and that provides change the corrector current as a function of power demand setting and the same corrector efficiency in the full range of the power demand loop performance.

The motor 6" drives the mag-slip I"' through the gearbox 8. The motor is switched on by two relays 5" which are connected with the amplifier output of the controller VII if it is used as reserved. While arising an unbalance at the output of the amplifier one of relays (it depends on the polarity of the unbalance) operates and switches on the motor which drives the mag-slip

eliminating the unbalance. The automatic setting corrector has a dead space exceeding that of the automatic controller. Switchings on the corrector while deviating a power level exceeding the corrector dead space are requited with constant redundant controller readiness to operate.

Control system description. The block diagram of the control system consisting of the described power demand loop, two channels of automatic power control and three channels of over-power-level control is shown in Fig.4.

There are independent ionization chambers for every channel. There are two identical amplifiers 18 in every over-power-level control channel. Signals from the common comparator 16 equal to the difference between the current of an ionization chamber and that of a power demand are fed to the inputs of the amplifiers connected in series. The outputs of the amplifiers are aranged in two-out-of-two coincidence circuit. In each amplifier a fault signal is identical with an over-power-level signal but under such circumstances there is no signal at the coincidence circuit output. When a signal of the second amplifier arises (because of a fault or over-power) the coincidence circuit generates a signal fed to the circuit of logic control of the rod drive system and holding electromagnets. The logic control circuit may release the electromagnets and switch on the motors of the rod drive system in an arrangement one-out-of-several or two-out-of several, for example out-of-three. The choise of a circuit depends on particular properties of the plant.

To increase the automation of the plant to a great extent both the rods of automatic controller and the shim rods control power and period. If the automatic controller rods while controlling approach the end of their permitted travel the shim rods are automaticaly switched on in the control system and move in the same direction as the controller rods do. Number of shim rods which are simultaneously in motion and the succession of their operation depend on a desired program. The shim rods travel untill the automatic controller rods return to their center position. Such an interrelationship of the rods results in increasing the effeciency of the controller units and may provide automatic

startup and changing the power of a reactor take care of depletion, poisoning, temterature and reactivity changes, while loading fuel elements in an operating reactor, that is such an arrangement of the rods automaticaly controls the reactor while disturbing the reactivity exceeded the automatic controller rods worthes.

While operated as discribed above the automatic controller actually drives a bank of rods which may insert an excess of reactivity far more than ß it is most important to consider the question of safety. Positive reactivity and the rates of its inserting while moving the bank of rods should be limited.

If the rods have approximately the same efficiency a bloking circuit is used to stop their travel when the number of the rods to be moved in the positive reactivity is more than that of permitted.

If the rods differ in efficiency there uses a circuit where the efficiency of every rod is taken into account and where the total effeciency of the rods to be moved out is evaluated. If the total rod efficiency exceeds the threshold of the circuit (a conventional threshold is 0.5÷0.8 ß) any move of the rods is blocked.

Relays in the automatic controller channels also provide the safety of the plant so as while arising great unbalances as a consequence of a fault in the channels these relays operate. They block the amplifier output and thus protect the reactor from false signals.

All these measures are taken to eliminate the opportunity of arising dangerous excess of reactivity.

<u>Reliability of the control system</u>. Reliability of the control system is provided by every channel duplicating, reserving, continuous and periodic checking of some devices, and increasing as much as possible reliability some units of the system at the expence of their possible simplification and application reliable elements. Any parameter is measured by no less than two independent devices with separate monitors.

Over-power-level measurements are made in no less than three independent channels. Measurements of the rate of power change

are made in no less than two independent channels. To avoid false operations in the operating range an emergency signal of the rate of power change is blocked. False operations are eliminated at the expense of coincidence circuits use. For example there are two amplifiers which outputs are arranged in "two.out-of-two" in every out of three independent channels of the over-power automatic protection (AP) system. Such a circuit gives an opportunity to dismantle devices for repair and transmit a control signal for checking without reducing reliability of the system.

Previously we have mentioned about reserving or in other words making use of redundancy of power demand loops. Analogously the power supplies of ionization chambers are reserved. If one of the power supplies connected in parallel faults the voltage at the power supply output is as before. One power supply may be used as a redundant for several ionization chambers.

Described system is reliable and simple at the same time. The system is reserved in such a way that it need not be through checked. Through circuits application makes the system complicated and may result in reducing its reliability. It is possible to use simple means of periodic or continuous checking the most important separate devices. Other elements which checking involves difficulties while fault cause shutdowns of the reactor. But the group of such elements is limited. One of said elements is holding rod electromagnets.

Reliable designing, correct checking before mounting and keeping the conditions of exploiting of these elements result in their almost absolute reliability. It were unjustified under such situation to complicate the system by means of designing circuits of through checking.

Reliability of the system has been increased a great deal at the expence of application transistors and magnetic amplifiers instead of valves. Nowadays there are a number of reactor control devices where transistors and magnetic amplifiers are used. Magnetic amplifiers are mainly used in power supply circuits to drive motors and electromagnetic clutches. Controlled rectifier

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circuits have also been designed for this purpose and they differ in simplicity and less gabarits of elements.

Reliability of the system is also increased at the expence of devices ability to operate in conditions of great mains voltage deviations. The mains voltage may be decreased by 30÷40%.

Noncontact elements are becoming more popular in control circuits. Circuits designed to drive the actuators and devices use transistors and logic elements (instead of relays and contactors). The logic elements used in the circuits are formed in moduluses which may be easily mounted on a conventional panel. These drive circuits are much more compact than that where relays and contactors are used.

In general control system completely consisted of noncontact elements were more bulky and complicated when maintanced (because of difficulties in finding defects) and as a result they were unsufficiently reliable systems. In every single case noncontact elements application should be reasonable. Quite a number of noncontact elements is conceived to be kept in the circuits for driving actuators, power demand loops, and correctors (these elements are designed to send commands pushbuttons, control keys as well as relays and contactors).

Results of the system test. Described system was tested in combination with a reactor simulator. As a result of testing the system has been considered capable for work.

Power deviations of the reactor simulator when one of the power demand loops is switched off do not exceed 2% of a fixed power level, errors in the over power control channels not exceeding 1% of the rated level. While changing power level within one range errors in the separate channels do not exceed 1% of the rated magnitude. While changing ranges power deviations do not exceed 1÷2% of a fixed level, errors in the over power control channels not exceeding 0.5% of the rated power. While mains +10 and -15% deviating power deviations do not exceed ±1% and when mains drops by 40% deviations do not exceed +3%.

Presently the described system is used for control a number of reactors including the material research reactor MRR (МИР).

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Conclusions. Designed system is universal because it may consist of different number of automatic control channels (up to 3) and over power control channels (up to 6) and besides it may accept outer signals providing different ways of reactor parameters control.

The system is automized to a great extent and as a result the operator pay less attantion to the system and that reduces a great deal the system reliability dependence on operator's experience.

Transistors, magnetic amplifiers, controlled rectifiers, transistor logic elements in combination with relays and contactors (in circuits of less importance) application has given an opportunity to design a reliable and comparatively simple system.

Channels duplicating and reserving separate the most important devices with simple periodic or continuous checking other separate devices has resulted in reliable system construction without through channels checking.

Designed system ensures safe operation of the system.

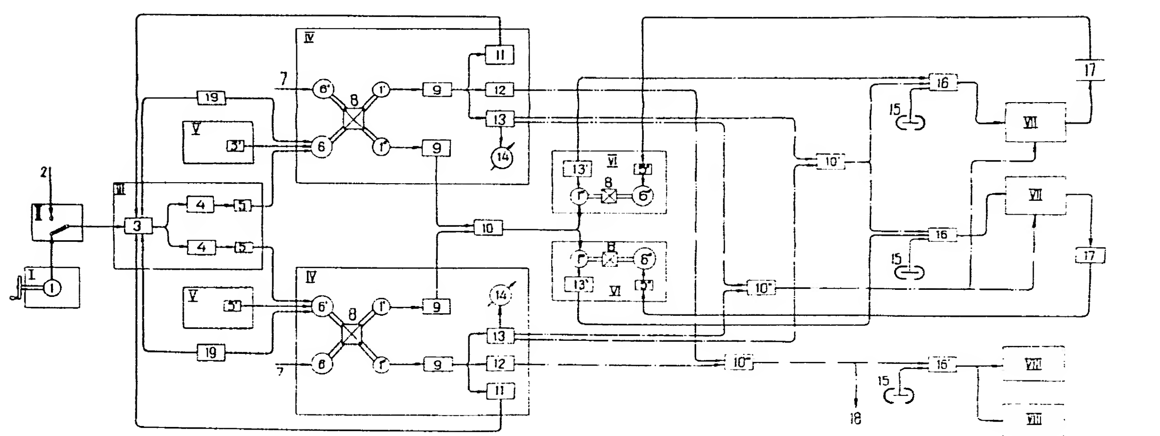

Fig.1. Block diagram of power demand loop

—·—·—·— power demand signal fed to automatic controller channels;
—··—··— signal of automatic controllers transmission factor control;
—···—···— power demand signal fed to over power channels.

I - settings unit; II - conditions selector; III - servo unit; IV - power demand circuit; V - power corrector; VI - automatic setting corrector; VII - controller amplifier; VIII - over-power control amplifier.

1 - mag-slip; 2 - signal of coolant flow demand loop; 3 - selector and comparator; 4 - servo amplifier; 5 - relay; 6 - motor; 7 - signal used for rapid power demand setting reduction; 8 - gearbox; 9 - ranges selector; 10 - circuit "or"; 11 - transformer; 12 - rectifier; 13 - transformer with rectifiers; 14 - power demand indicator; 15 - ionization chamber; 16 - comparator; 17 - circuit of selection "operation - reserve"; 18 - signal fed to other over power control channels; 19 - manual control key of power demand circuit.

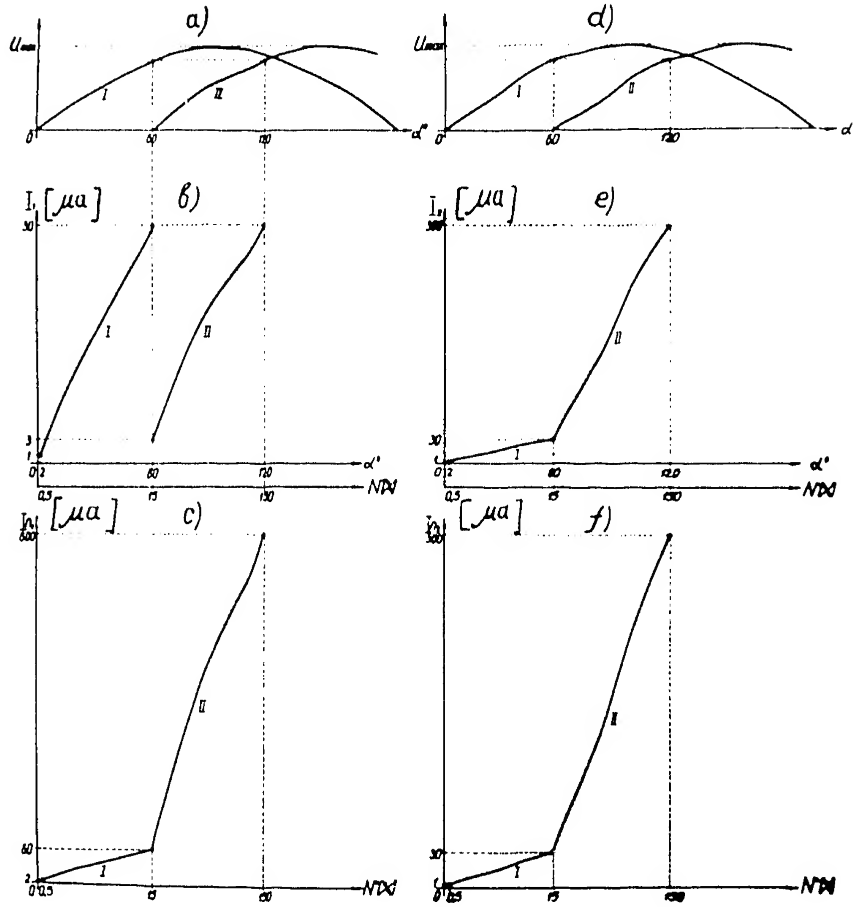

Fig. 2. a) and d) mean voltage between mag-slip phases U as a function of angle of rotation α° ; b) and e) power demand currents I_1 and I_2 as functions of angle α° and power demand level N' for automatic power controller and over power control channels respectively; c) and f) currents of ionization chambers I_{n_2} and I_{n_2} as functions of reactor power N" for automatic power controller and over power control channels respectively.

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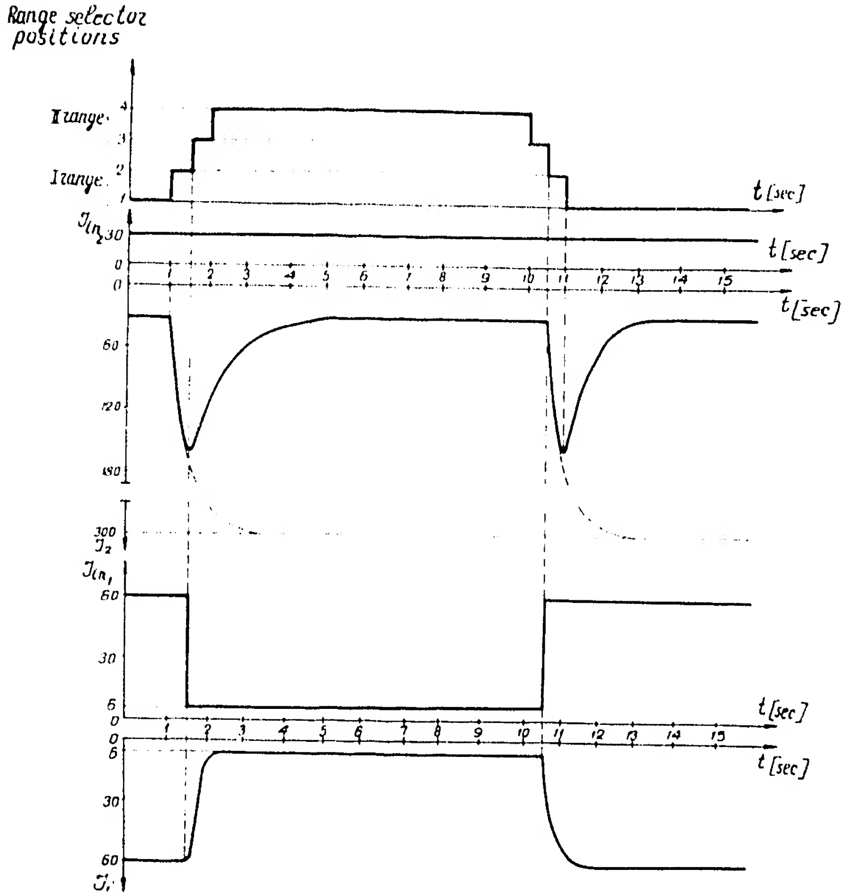

Fig.3. Curves of power demand current change (I_1 and I_2) and amplifiers input currents (I_{in_1} and I_{in_2}) while changing ranges. 1 and 4 - basic 2 and 3 - intermediate positions of range selector. I_1 and I_{in_1} - for automatic control channels. I_2 and I_{in_2}- for over power control channels. The time of range selector being in intermediate positions is taken 0.5 sec.

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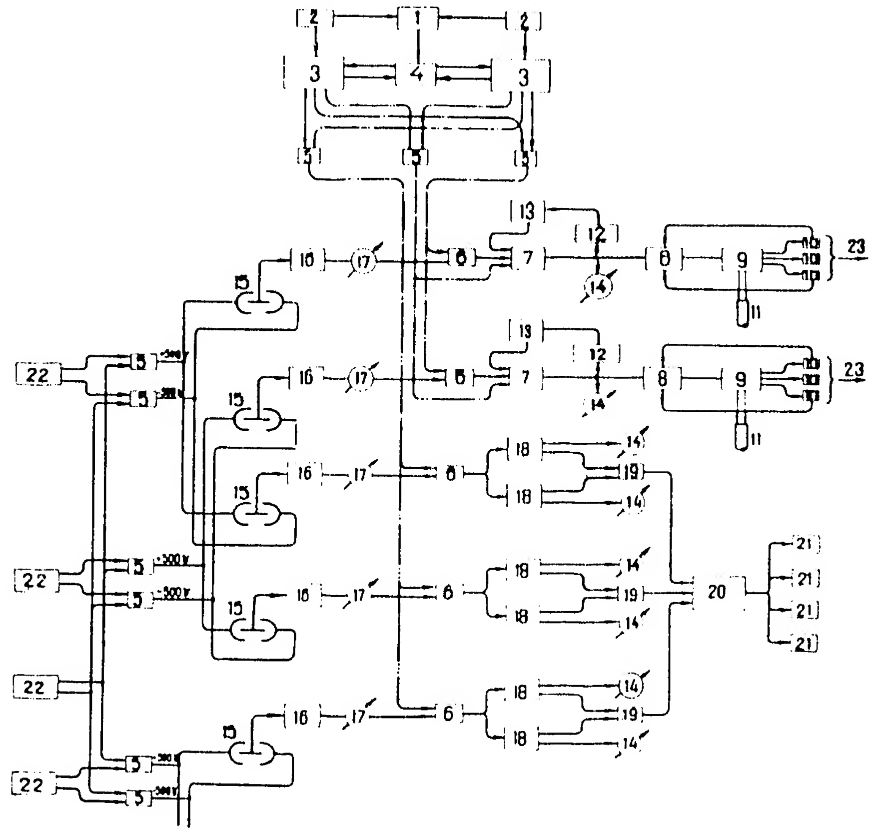

Fig.4. Block diagram of control system.

1 - unit of settings; 2 - manual control key of power demand circuit; 3 - power demand circuit; 4 - servo unit; 5 - circuit "or"; 6 - comparator; 7 - controller preamplifier; 8 - controller output amplifier; 9 - automatic controller servo drive; 10 - monitors of ultimate and intermediate rod positions; 11 - automatic controller absorptive rod; 12 - circuit of selection "operation - reserve"; 13 - automatic setting corrector; 14 - unbalance indicator; 15 - ionization chamber; 16 - ionization chamber current corrector; 17 - ionization chamber current indicator; 18 - over power control amplifier; 19 - coincidence circuit "two-out-of-two"; 20 - logic circuit of motors and holding electromagnets drive; 21 - holding electromagnets of safety rods; 22 - power supply circuit of ionization chambers; 23 - control system of shim rods coupling.

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Descriptions in Figures

Fig. 2. a), b), c), d), e), f)

I_1 [μa] , I_2 [μa]

I_{n_1} [μa] I_{n_2} [μa]

Fig. 3. Range selector positions

II range

I range

t - sec

I_{in_2} [μa]

I_2 [μa]

I_{in_1} [μa]

I_1 [μa]

t - sec

Fig. 4. + 500 v.

- 500 v.